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From U. S. Department of Commerce, Joint Publications Research Service, JPRS: 37,560, 13 September 1966

UDC 532.595.2

ON INFLUENCE OF HYDROSTATIC PRESSURE ON PARAMETERS OF UNDERWATER EXPLOSION

/Following is a translation of an article by F. A. Baum, N. S. Sanasaryan in the Russian-language periodical Fizika Goreniya i Vzryva (Physics of Combustion and Explosion) No. 4, Nauka Publishing House, Siberian Branch, Novosibirsk, 1965, pages 52-62./

Movement of Gas Area in Water with Hydrostatic Pressure p_0 taken into consideration

In accordance with the numerous experiments, a dependence of pressure on a specific volume for explosion products (PV) is expressed by two adiabatics:

$$p V^k = \text{const} \tag{1}$$

for $p > p_k$, и

$$p V^\gamma = \text{const} \tag{2}$$

for $p < p_k$,

where $k = 3, \gamma = 7/5$. A value p_k (a pressure at which two adiavatics conjugate) is determined from energy considerations

$$E_{\text{ои}} = \int_{V_н}^{\infty} p d V = \int_{V_н}^{V_k} p d V + \int_{V_k}^{\infty} p d V, \tag{3}$$

where $V_н$ is the initial specific volume of PV; V_k is a specific volume PV, corresponding to the pressure p_k.

Substituting (1) and (2) in (3) we obtain after some simple transpositions

$$p_k = p_н \left\{ \frac{\gamma - 1}{k - \gamma} \left[\frac{(k - 1) E_{\text{эн}}}{p_н V_н} - 1 \right] \right\}^{3/2}, \tag{4}$$

where $p_н = \frac{1}{8}\,{}_{bb}\,D^2$ is the value of initial mean pressure in PV; $E_{вв}$ is energy of explosive substances with respect to a volume unit.

Since the pressure in explosive products drops substantially beginning with the expansion radius $R = R_k$, we may consider water as a non-compressed liquid and express its movement under the action of explosive products by the equations for movement of non-compressed liquid in the form of Euler:

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial r} = -\frac{1}{\rho_0}\frac{\partial p}{\partial r}, \tag{5}$$

$$\frac{1}{r^2}\frac{\partial}{\partial r}(r^2 v) = 0. \tag{6}$$

The marginal conditions are

$$r = \infty, \quad p = p_0, \tag{7}$$

$$r = R, \quad p = p_{(R)} = p_н\left(\frac{R_0}{R_k}\right)^9\left(\frac{R_k}{R}\right)^{21/5}. \tag{8}$$

The solution for the velocity of gas area expansion appears as:

$$v^2 = \left(\frac{R_k}{R}\right)^3\left\{V_k^2 + \frac{5p_k}{3\rho_0}\left[1 - \left(\frac{R_k}{R}\right)^{6/5}\right]\right\} - \frac{2p_0}{3\rho_0}\left[1 - \left(\frac{R_k}{R}\right)^3\right]. \tag{9}$$

By inserting in the formula (9) $v = 0$ and neglecting small members, we obtain the following expression for the maximal radius of gas area expansion:

$$R_м = \left(\frac{p_н}{p_k}\right)^{1/9}\left(\frac{5p_k}{2p_0}\right)^{1/3} R_0. \tag{10}$$

The ratio for the expansion velocity (9) will appear as

$$v = \frac{dR}{dt} = \sqrt{\frac{2p_0}{3\rho_0}}\left[\left(\frac{R_м}{R}\right)^3 - 1\right]^{1/2}. \tag{11}$$

By integrating (11) from $R = R_o$ to $R = R_m$ we obtain a maximal time for the expantion of a gas area:

$$t_м = \left[\frac{\sqrt{\pi}}{3}\frac{\Gamma\left(\frac{6}{5}\right)}{\Gamma\left(\frac{4}{3}\right)} - \frac{2}{5}\left(\frac{R_0}{R_м}\right)^{5/2}\right]\sqrt{\frac{3\rho_0}{2p_0}}\cdot R_м, \tag{12}$$

where $\Gamma\left(\frac{5}{6}\right)$ и $\Gamma\left(\frac{4}{3}\right)$ is a gamma-function,

The obtained ratios of (10) and (12) show that

$$R_м = \frac{A}{p_0^{1/3}},$$

$$t_м = \frac{B}{p_0^{5/6}}.$$

These types of dependencies were obtained before /1-4/. However, as we shall show below, the ratios (11) and (12) produce more precise values of coefficients A and B and, consequently, a better conformity with the experiment.

Influence of p_o on the Initial Parameters of a Shock Wave

At the initial (hydrostatic) pressure in 1,000 atmospheres, a density of water is less than the density of spreading out explosive products, therefore, under the impact of the latter on the water, a shock wave will move in the water and a rarefied wave will move in the explosive products. The conditions of equality of pressures and mass velocities at the boundary line between the explosive substance and the water give us the following equations for finding the initial parameters of the shock wave /3/:

$$v_x = \frac{1}{4}\left[4 - 3\left(\frac{p_x}{p_н}\right)^{1/3}\right] D, \tag{13}$$

$$v_x = \sqrt{\frac{p_x - p_0}{\rho_0}\left[1 - \left(\frac{p_x}{3940} + 1\right)^{-1/n}\right]}. \tag{14}$$

These equations may be solved better in a graphical manner (fig. 1.)

The estimates show that with the increase of p_o for each 100 atmospheres, the peak pressure of the shock wave increases, on the average, by .4 percent, the mass velocity at the front is decreased by .3 percent, and the shock wave velocity increased by .7 percent.

Dependence of Intensity of a Shock Wave on p_o

We shall use the methods of the theory of similarity and dimensionality. A respective change of a volume of $\frac{\Delta V}{V}$ of a medium at a given point will be equal to

$$\frac{\Delta V}{V} = \beta_s \cdot \Delta p, \tag{15}$$

where Δp is the change of pressure at a given point.

The value β_s is idiabatic compressibility characterizing a

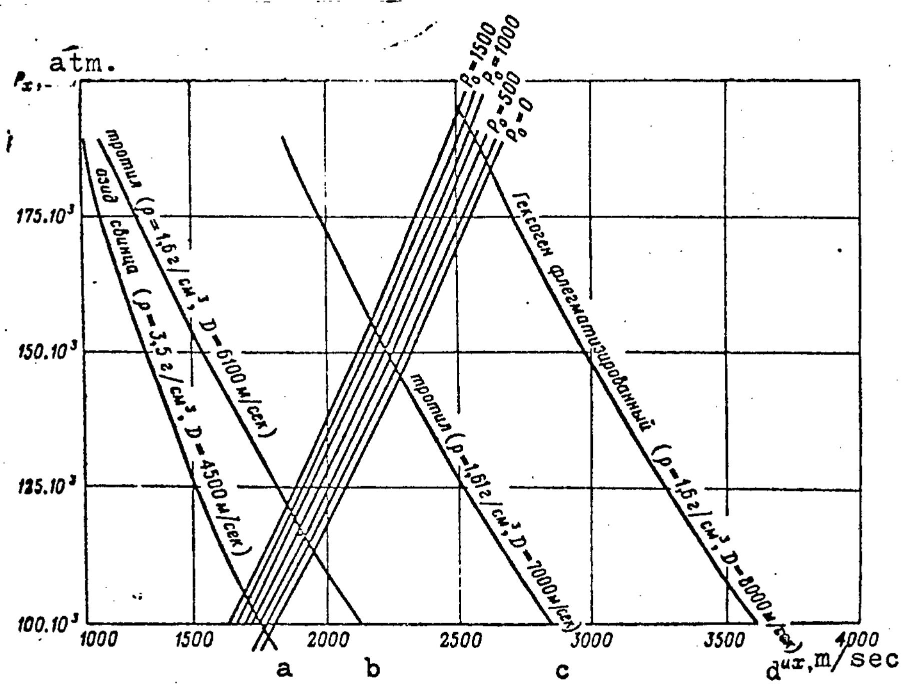


Fig. 1.

a. lead azide ($\underline{p}$ = 3.5 g/cu cm, $\underline{D}$ = 4,500 m/sec

b. trotyl ($\underline{p}$ = 1.6 g/cu cm, $\underline{D}$ = 6,100 m/swc

c. trotyl ($\underline{p}$ = 1.61 g/cu cm, $\underline{D}$ = 7,000 m/sec.

d. hexogene phlegmatized ($\underline{p}$ = 1.6 g/cu cm, $\underline{D}$ = 8,000 m/sec

respective change of the system volume at an adiabatic decrease of its pressure per unit

$$\beta_s = -\frac{1}{V}\left(\frac{dV}{dp}\right)_s \qquad (16)$$

We know from thermodynamics that

$$dE = -pdV + TdS.$$

Hence, the mean compression of the medium by explosion will be equal to

$$\left(\frac{\overline{\Delta V}}{V}\right) = \beta_s \frac{\rho_{BB} Q_{BB} R_0^{\nu}}{R^{\nu}}, \qquad (17)$$

where ρ_{BB} is density of explosive substance; Q_{BB} is specific heat of explosion; R_o is the radius of charge; ν = 1, 2, 3, respectively, for flat, cylindrical and spherical shock waves.

Since a respective compression at the point is a function of a mean compression of the medium, then

$$\beta_s \Delta p = f\left(\sqrt[\nu]{\beta_s \rho_{BB} Q_{BB}} \frac{R_0}{R}\right). \qquad (18)$$

According to a large number of experimental and theoretical investigations, this function well approximates in the form of a power dependence

$$\Delta p = \frac{1}{\beta_s}\left(\sqrt[\nu]{\beta_s \rho_{BB} Q_{BB}} \frac{R_0}{R}\right)^{\alpha} \qquad (19)$$

or

$$\Delta p = \Delta p_0 \left(\frac{R_0}{R}\right)^{\alpha} \left(\frac{\beta_{0s}}{\beta_s}\right)^{\frac{\nu - \alpha}{\nu}}, \qquad (20)$$

where Δp_o = Δp at p_o = 1 atmosphere, $R = R_o$; $\beta_{os} = \beta_s$ at p_o = one atmosphere.

Let as teke the equation of a state of water in the form of

$$p = B(S)\left[\left(\frac{V_0}{V}\right)^n - 1\right], \qquad (21)$$

then

$$\beta_s = -\frac{1}{V}\left(\frac{\partial p}{\partial v}\right)_s = \frac{V_0}{Bn}\left(\frac{p}{B} + 1\right)^{-1}. \qquad (22)$$

Since $B \gg 1$ kg/sq meter (for water $B \approx 3{,}000$ kg/sq meter,) then

$$\beta_{0s} = \frac{V_0}{Bn}: \qquad (23)$$

By using (22) and (23), we express the equation (20) in the form

$$\Delta p = \Delta p_0 \left(\frac{R_0}{R}\right)^a \left(\frac{p_0}{B} + 1\right)^{\frac{v-a}{v}}. \tag{24}$$

The obtained relation (24) at a certain value of coefficient of the peak pressure reduction solves completely the question of influence of p_o on p.

By considering the obtained data on influence of p_o on p at $R = R_o$, we may determine the value $\frac{v - a}{v}$ from the relation (24) as well as the value in a direct proximity from the charge. The obtained values for various explosive substances with ρ_{BB} = = 1.6 g/ cu cm, D = 7,000 meters per second are very close and are equal to:

a = 2.58 for v = 3

a = 1.72 for v = 2

a = .861 for v = 1

Dependence of Impulse of Underwater Explosion on p_o

In accordance with the theory of detonation, the formula [3] is true for impulse flow passing through a unit of area at the distance of radius of the charge:

$$i = \frac{16}{27} \cdot \frac{\sqrt{M_{BB} E_{BB}}}{4\pi R_0^2}. \tag{25}$$

Since at the explosion 's designed energy the impulse increases proportionally to the square root of the mass engaged in the motion, then at the distance of r from the charge

$$i = \frac{MD}{27\pi r^2} \sqrt{1 + \frac{M_e}{M_{BB}}},$$

or

$$i = \frac{4}{81} \rho_{BB} D^2 R_0 \left(\frac{R_0}{r}\right)^2 \sqrt{1 + \frac{M_e}{M_{BB}}}. \tag{26}$$

By expressing the values of the masses of water and explosive substances by means of their volume and density, we shall obtain

in the interval of $R_0 < r < R_n$

$$i = \frac{4}{81} \rho_{BB} D R_0 \left(\frac{R_0}{R}\right)^2 \sqrt{1 - \frac{\rho_0}{\rho_{BB}} + \frac{\rho_0}{\rho_{BB}} \left(\frac{r}{R^0}\right)^3}, \tag{27}$$

in the interval of $r \geqslant R$

$$i = \frac{4}{81} \rho_{BB} D R_0 \left(\frac{R_0}{r}\right)^2 \sqrt{1 + \frac{\rho_0}{\rho_{BB}} \left(\frac{R_м}{R_0}\right)^3 \left[r \left(\frac{r}{R_м}\right)^2 \quad 3\left(\frac{r}{R_м}\right) + 1\right]}. \quad (28)$$

The variation of the impulse with the distance for p_o = 1 kg. per sq. cm and p_o = 1,000 kg/sq sm is shown in fig. 2.

From the formula (28) at distances $R \gg R_м$

$$i = \frac{4}{81} D \rho_{BB} R_0 \sqrt{\frac{3\rho_0}{\rho_{BB}}} \left(\frac{R_м}{R_0}\right)^{1/2} \left(\frac{R_0}{r}\right). \quad (29)$$

Since $R_м \sim \frac{1}{p_0^{1/3}}$, then

$$i \sim \frac{1}{p_0^{1/6}}. \quad (30)$$

Thus p_o exerts the greater influence on the explosion impulse, the farther it is from the charge.

Dependence of Shock Wave Energy on p_o

The dependence $R_м = f(p_0)$ permits us to determine the influence of p_o on energy of the shock wave.

Let us compose a balance for the energy of explosive substances:

$$E_{BB} = E_{yв} + E_п + A_{p_0} + E_{ocт}, \quad (31)$$

wher E_{yb} is energy of shock wave; E_n is energy of the spreading out water flood; A_{po} is work for overcoming p_o; E_{oct} is remaining energy of explosive products.

At $R = R_m$ we have

$$E_п = 0,$$

$$A_{p_0} = \frac{4}{\pi} (R_м^3 - R_0^3) p_0.$$

$$E_{ocт} = \frac{4}{3} \pi R_м^3 \frac{p(R_м)}{\gamma - 1},$$

where $p(R_m)$ is the pressure in the explosive products at $R = R_m$. By substituting these relations in (31) and using the expression for R_m, we obtain

$$\frac{E_{yв}}{E_{BB}} = 1 - \frac{p_0}{\rho_{BB} Q_{BB}} \left\{\left(\frac{p_н}{p_k}\right)^{1/3} \left(\frac{5p_k}{2p_0}\right)^{3/5} \left[\left(\frac{5p_k}{2p_0}\right)^{2/5} + 1\right] - 1\right\}. \quad (32)$$

Fig. 3 shows this dependence for trinitrotoluene with Q = = 1,459 ccal/kg; ρ_{BB} = 1,67 g. cu cm (the given explosive substance was used for the experiments the results of which are shown below.)

As seen from fig. 3, at p_o = 1,500 kg/sq cm in comparison with p_o = one atmosphere, the energy of the shock wave diminishes by 25 percent.

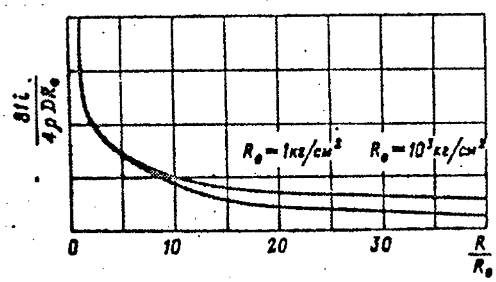


Fig. 2

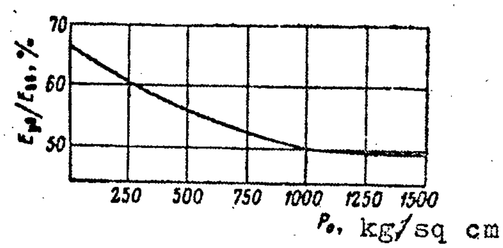


Fig. 3

Experimantal Investigation of Influence of p_o on the Parameters of Underwater Explosion

The experiments were conducted in a high pressure installation (autoclave,) 350 mm of inside diameter. The autoclave had two optical inlets of 50 mm diameter, in the form of a cylinder made of organic glass. The autoclave was filled with water, with an air cushion of from 50 to 100 mm thick left at the top. The air compressor kept the pressure at 400 atmospheres.

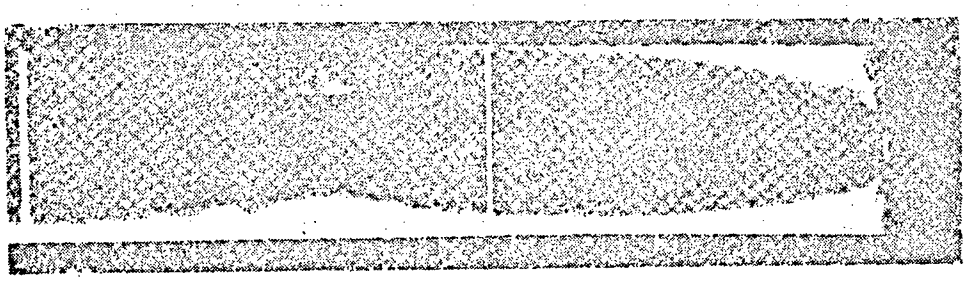


Fig. 4

The charges of spherical and cylindrical forms were placed in the center of the autoclave opposite the windows to permit taking the picture of the whole radius of the bubble pulsation. The charges were made of trinitrotoluene pressed to density of 1.67 g/cu cm. To seal them hermetically, they were covered with a layer of epoxy resin. The spherical charge weighed .72 giga- and was 10 mm in diameter; the cylindrical charge weighed 1.72 giga-, 6 mm in diameter and its length equaled to the six diameters. A piece of lead nitride of 5 or 7 percent of the charge's full weight and a little amount of TNT

powder were used as a detonator.

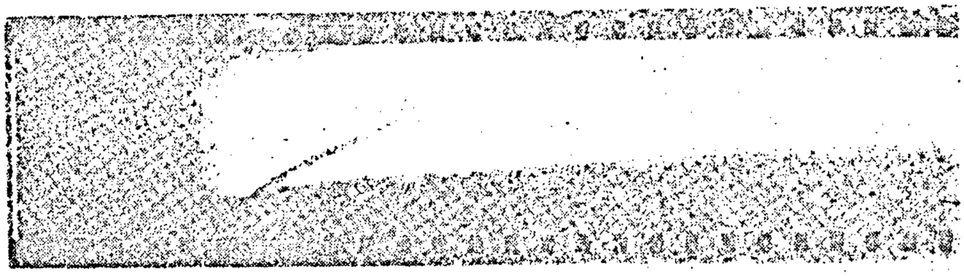


Fig. 5

A spectrophotometric installation was used to photofraoh the process at 7,500 revolutions per minite for the investigation of a gas bubble pulsation and at 45,000 revolutions per minute for registering the shock wave. The picture of the bubble evolution (at p_o = 400 atmospheres) at the explosion of the spherical charge is chown in fig. 4; fig. 5 shows the registration of the shock wave's trace (at p_o = 100 atmospheres) at the explosion of the cylindrical charge.

Fig. 6 shows the diagram of synchronization of the moments of subexplosions of the charges and flashes of the impulse lamp.

A high-voltage impulse was sent from the control panel of the photometric installation directed toward the impulse lamp to ignite it and toward the discharger "p", through which the capacity C_1 was discharged to resist the detonator line. The length of underglow was selected depending on the period of the gas bubble pulsation. The time length was regulated by a value of battery capacity of C_2. The experiments were conducted in water up to the hydrostatic pressure p_o = 400 atmospheres for each 100 atmospheres.

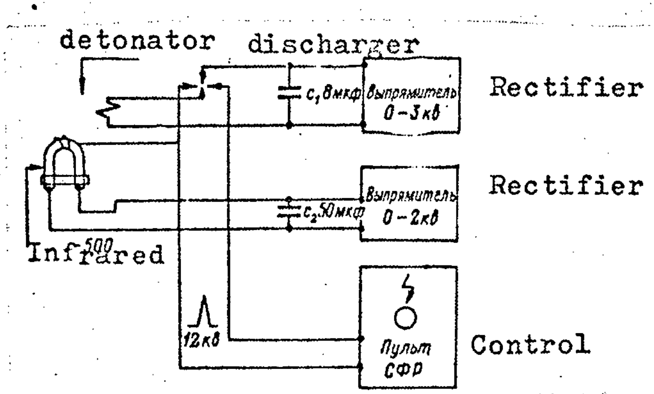


Fig. 6

Figures 7 and 8 show diagrams of dependence $\underline{R}(\underline{t})$ at the time of explosions of the cylindrical and spherical charges for p_o = 100, 200, 300, 400 atmospheres.

As fig. 9 shows, the dependence of log $\frac{R_m}{R_o}$ on log p_o corresponds to the right angle slope $\alpha = 1/3$, both for the spherical and cylindrical charges.

The latter is explained by the fact that for the cylindrical charges with $H/d = 6$ (H is the charge's height, d, its diameter) the time for the maximal expansion of the gas bubble was so great, that during this period the scattering front of the explosive product was able to take on the spherical form.

The dependence $\frac{R_m}{R_o} = f(p_o)$ is expressed by the formula:

$$\frac{R_м}{R_0} = \frac{A}{p_0^{1/3}}, \tag{33}$$

where $A = 36.3$ and $A = 511$ for the spherical and cylindrical charges (p_o is substituted in k Giga/sq cm.)

The theoretic value of A for the spherical explosion is calculated by (10) and equals 37.2. According to O. E. Vlasov /4/, the values of A are equal to 45 and 20.2, respectively.

The dependence log T on log p_o corresponds to a line with the incline $= \frac{5}{6}$ (fig. 10.0

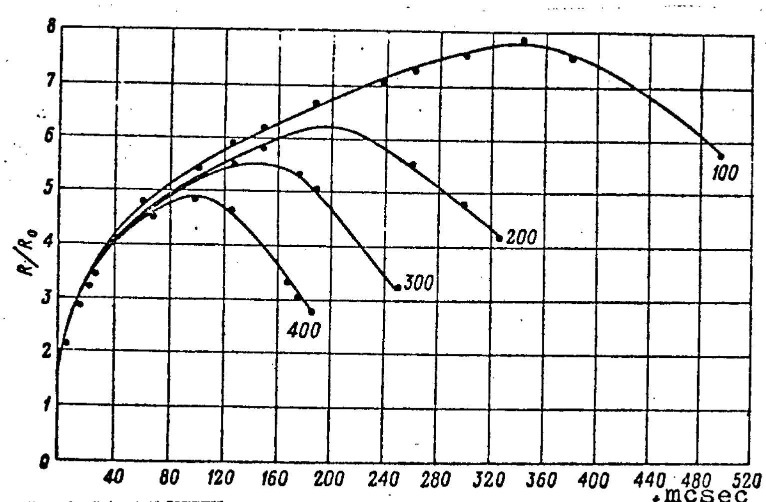


Fig. 7

The dependence $T = f(p_o)$ is expressed by the formula

$$T = \frac{B}{p_0^{5/6}}, \tag{34}$$

where $\underline{B}$ = 15.4 μ sec for the spherical explosion; $\underline{B}$ = 18μ sec for the cylindrical explosion.

The theoretical value of $\underline{B}$ for the spherical explosion, in accordance with (12) equals 16.6 μ sec; according to Vlasov /4/, $\underline{B}$ = 24.1μ sec.

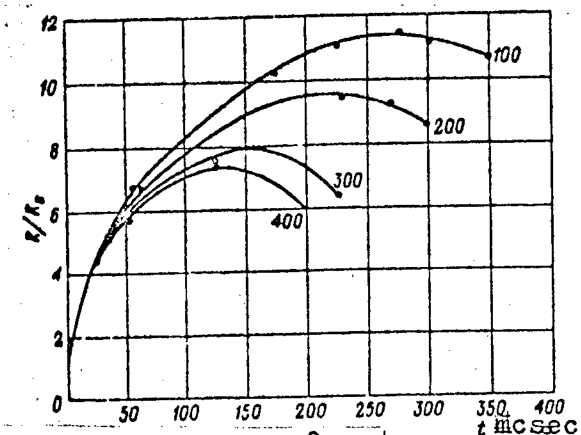


Fig. 8

Fig. 11 shows the dependence of a dimensionless distance $\sqrt[3]{\frac{R_м - R_0^3}{R_м^3 - R_м^0}}$ of the gas bubble expansion on a dimensionless time $\underline{t}/\underline{T}$ for the spherical explosion; fig. 12 shows the respective dependence $\sqrt[3]{\frac{R^2 \quad R_0^2}{R_м^2 - R_2^0}}$ on $\underline{t}/\underline{T}$ for the cylindrical explosion.

The other series of experiments delt with the registration of $\underline{r}(t)$ for the shock wave front. This dependence permitted to proceed /5/ to a dependence of a distribution velocity of the shock wave front on $\underline{r}/\underline{R}_o$, and also, by a shock adiabatic for water /1, 3, 6/ to a dependence of the pressure on the shock wave front at a distance of $\Delta \underline{p} \left(\frac{\underline{r}}{\underline{R}_o}\right)$. This dependence is expressed with sufficient precision by power functions with exponents different for different intervals.

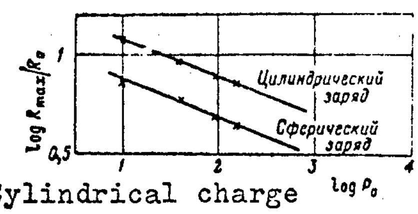
For the spherical charge

$$\Delta p = 125 \cdot 10^3 \left(\frac{R_0}{r}\right)^{2,55} (\kappa\Gamma/c\text{м}^2) \qquad (35)$$

at $1 < \frac{r}{R_0} < 2$,

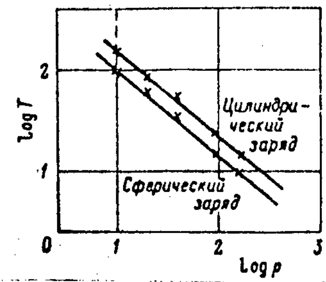
$$\Delta p = 85,5 \cdot 10^3 \left(\frac{R_0}{r}\right)^2 \qquad (36)$$

at $2 < \frac{r}{R_0} < 7$.



Cylindrical charge
Spherical charge

Fig. 9



Cylindrical charge
Spherical charge

Fig. 10

For the cylindrical charge

$$\Delta p = 125 \cdot 10^8 \left(\frac{R_0}{r}\right)^{1,7} \qquad (37)$$

at $1 < \frac{r}{R_0} < 3,$

$$\Delta p = 72,5 \cdot 10^8 \left(\frac{R_0}{r}\right)^{1,2} \qquad (38)$$

at $3 < \frac{r}{R_0} < 15.$

From the formulas (35) and (36) it is evident that the experimentally established (for the nearest distances from the point of explosion) values of the index $\underline{a}_{exp}$ approximate well its estimated values arising from (24.)

The spherical explosion: $\underline{a}_{exp} = 2.55$; $\underline{a}_{est} = 2.58$.

The cylindrical explosion: $\underline{a}_{exp} = 1,70$; $\underline{a}_{est} = 1.72$.

In the investigated intervals of variation $\frac{r}{R_o}$ hydrostatic pressure p_o up to 400 atmospheres hardly shows influence on the front pressure; or, rather, this influence, according (24) is so small that it lies within the experimental errors.

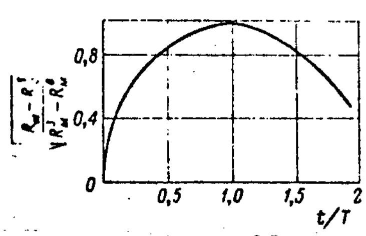


Fig. 11.

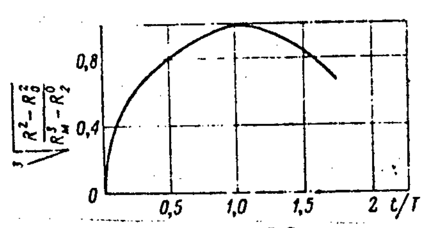


Fig. 12.

Conclusions

1. Hydrostatic pressure p_o influences essentially the maximal radius and time of the gas area expansion:

$$R_м \sim \frac{1}{p_0^{1/4}},$$

$$t_м \sim \frac{1}{p_0^{5/6}}.$$

2. Initial parameters of the shock wave, irradiated in the water at the time of an underground explosion under the conditions of increased hydrostatic pressures depend but little on p_0.

3. The rate (24) is determined for the influence of p_0 on Δp, according to which this influence becomes the stronger the farther it is from the charge.

4. A possibility of a theoretic calculation of a dampening coefficient a at a distance intermediately close to the charge has been shown.

3. According to (32,) (27,) and (28) the higher is hydrostatic pressure p_0 the smaller is a part of energy of an explosive substance passing into a shock wave and in a total specific impulse of an underground explosion. The influence of p_0 on the impulse, with the increase of distance $r \gg R_м$ tends toward a dependency

$$i \sim \frac{1}{p_0^{1/4}},$$

which at the higher hydrostatic pressures of the order of 1,000 atmospheres leads to the decrease of the impulse three times and more.

Received 10 May 1965.

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